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ELECTRIC GENERATION
HOME WOOD-FIRED
STEAM ENGINE

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Prepared for

MONTANA DEPARTMENT of NATURAL RESOURCES and CONSERVATION

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ELECTRIC GENERATION HOME WOOD-FIRED STEAM ENGINE

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September, 1983

Prepared for

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PROJECT ABSTRACT

The objective of this project is to test and demonstrate a home power system ideally suited to the Eureka area of Montana and others with similar conditions. Many home sites in the mountains are too sheltered for wind power, and water power is limited to those few sites that have access to a higher elevation water source. Solar power for heating purposes has limited value in the Eureka area because the sky is generally overcast in winter. Many homesites don't have access to commercial electricity. Wood-fired steam power was chosen as a power source because it can be used wherever wood is available.

This project is limited to demonstrating the suitability of wood for generating electricity. Although not analyzed in this study, several methods can use the waste heat from wood-fired generation for home heating. Such multiple use of the energy would be ideal for obtaining the greatest benefit.

The system as used in this project consists of a wood-fired power boiler providing steam to a custom built 0-5 H.P. steam engine or steam turbine driving a 12 volt automobile alternator. Also included are control devices for water, steam, and electricity. The power is stored in deep cycle batteries.

The home used to test this system is wired for dual voltage, and has a wide variety of appliances designed or adapted to operate on the 12 volt D.C. power that this system will produce.

All labor for the project was donated by the applicant except for a portion of the steal fabrication for the firebox. That portion was performed under contract.

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BACKGROUND INFORMATION

Steam was once used extensively as a source of mechanical power, particularly in areas abundant with wood fuel. Steam powered lumber mills were fairly common in Montana. Now with the decreasing supply and increasing cost of power, steam power is worth investigating again. Steam power technology has been around for a long time, and this project doesn't involve any new technology. It is, however, a relatively new application. There is very little equipment available in this small size, and most of the previous research and application has involved larger systems.

Thanks to the recreational vehicle industry, there is already a wide variety of household items available to run on 12 volts D.C. A partial list includes: lights (both fluorescent and incandescent), television, stereo, vacuum cleaners, radios, clocks, water pumps, refrigerators, sewing machines, electric razors, and fans. This makes it possible to operate many items directly with 12 volt storage batteries. Also, D.C. to A.C. inverter technology has reached a high level. Efficiency ratings of modern units are in the area of 90%. The use of invertors make it possible to use those items that are not adaptable to operate on 12 volt D.C.

Although the capacity of this system is relatively small, the principles and methods used can be adapted to almost any size desired. This makes the system not only useful for low energy use homes, but for more conventional homes as well. The steam generator could easily be scaled up to produce 5000 watts, and inverters are also available to handle that much power and more. Large systems, however, would require tremendous amounts of wood, and therefore would only be feasable where there are wastewood products to be disposed of. Generating at the rate of 5000 watts would require 325 pounds of wood per hour.
A major portion of this project was research. Of particular importance was locating suitable components for this size system, and matching the numerous components to work properly and safely together.

High pressure steam can be very dangerous, and anyone considering using steam power should research the field throughly in order to operate the system safely and to know how to prevent accidents if anything fails. It can not be over emphasized that the system must be designed for safety, and the operator must be thoroughly competant.

Technical background for this project came from the following sources:

Libraries Searches:

- Kalispell Public Library, Kalispell, MT
- Lincoln County Public Library, Eureka, MT (obtained materials nationwide through interlibrary loan)
- Fort Wayne Public Library, Fort Wayne, IN
- Seattle Public Library, Seattle, WA
- University of Washington, Seattle, WA
- (individual books and magazines are listed in the appendix)

Industry Contacts:

- Semple Engine Co., St Louis MO
- Carling Turbine Co., Worchester, MA
- Tiny Power, Tehachapi, CA
- Cast Corp., Benton Harbor, MI
- Caldwell Industries, Luling, TX
- Therma-Volt, Republic, WA
- Coles Power Models, Ventura, CA
- Hydraulic & Air Equipment, Seattle, WA
- Exide Industrial Battery Division, Horsham, PA
- numerous boiler manufactures and dealers

Personal Contacts:

- Fred Seaton, Republic, WA
- Bill Durham, Seattle, WA

TECHNICAL DESCRIPTION

The intent of this project was to build, test, and demonstrate a wood-fired steam power system designed to produce 12 volt power at up to 120 amps to charge a battery bank to provide the electrical needs for a 500 KWH per year cosumption rural home. Costs were kept as low as possible to demonstrate that such a system is within reach of rural residents who might benefit from such a system. The original design was based on a home built vertical fire-tube boiler equipped with a wood burning firebox. The steam would power a small 10 H.P. turbine (actually a rotary vane-type motor) that would drive two 60 amp alternators. The exhaust steam would be condensed back into water and returned to the boiler to reduce water consumption.

Quite a few changes were made as the project progressed. The plans to build the boiler were abandoned. It was found to be too difficult to get a non-standard boiler design passed by the Montana Boiler Board. The requirements are quite strict in an effort to prevent boiler accidents. Although the boiler design was sound, it would have been necessary to hire a certified engineer to certify that the design met the code requirements. Instead, a used boiler was purchased and a firebox built for it.

The item being sold as a steam turbine was found to actually be a compressed air motor, and the manufacturer did not believe that it could be used for steam. It might have been possible to modify it to make it suitable, but at a price of $800 it was too much to risk. Instead, two other engines were tested: A piston engine and an industrial turbine; both built specifically for steam.

The steam condenser was abandoned because the saving in water wasn't worth the technical difficulties involved (a cooling pond would have been required). Also, it was found that the piston engine required some lubrication for the valve, and the oil in the exhaust steam makes it unsuitable to return to the boiler.

The electrical capacity of the system was dropped from 120 amps to 60 amps for two reasons. The piston engine and boiler performed more smoothly and more efficiently at lower output, and the 400 A.H. battery bank was better suited to lower output. In fact, for most of the charge cycle, output must be below 60 amps to prevent excessive voltage.

There are four major components to the system:

1. The boiler assembly including the firebox and steam pressure, water, and draft controls.

2. The steam engine. Both a piston engine and a turbine were used and tested.

3. The mechanical drive system and alternator.

4. The feedwater pump and controls.

The boiler is a commercial unit manufactured by Eclipse Lookout Co. and carries A.S.M.E. and National Board Certification. It is a vertical firetube type that is rated at 125 psi working pressure and produces up to 241 pounds of steam per hour. The boiler shell is 3/8" thick, 24" diameter, and 29½" high. It contains 112 1" tubes and one 2" tube (to accomodate a fuseable plug). There are four hand-holes for inspection and cleaning. The shell is insulated with one inch of fiberglass.

The boiler was originally equipped with a gas burner which was replaced with a wood-burning firebox. The firebox is 30" long, 28" wide, and 25½" high. In addition, there is a 26" diameter cylindrical section added on top of the firebox (between the firebox and boiler shell). The purpose of this section is to increase the combustion space so that complete combustion will occur before the gases enter the firetubes. The firebox and extention are both lined with firebrick and/or insulating refractory (which has 12 times greater insulation value than firebrick).

The boiler system also includes the following:

1. Three gauge cocks and a water gauge glass for monitoring water level.

2. A McDonnell float switch to control feedwater to maintain proper water lever in the boiler. The float switch also contains a switch to operate a low water level alarm.

3. A 125 psi relief valve to prevent excess pressure.

4. A draft controller which is operated by a small pressure cylinder. Boiler pressure will extend the piston, and a counteracting spring will retract it. The piston is attached to the draft flap with a chain. As pressure increases, the piston is extended to close the flap. As pressure drops, the spring retracts the piston and causes the flap to open. This system controls pressure to within 5 psi. Boiler pressure is indicated by a 0-160 psi gauge.

5. A blowdown valve for daily cleaning and draining of the boiler.

Two engines were used. The piston engine is an experimental prototype built by Therm-A-Volt Company. It is a single cylinder, single acting engine with 3½" bore and 5" stroke. It was designed to eliminate the need for cylinder oil by using teflon piston rings. Main bearings are heavy duty pillow blocks with sealed ball bearings. They support a 1½" main shaft with a 19" flywheel-pulley on one end and an 8" flywheel on the other. The 8" flywheel also holds the crank pin which has a sealed ball bearing for the rod bearing. The cylinder is steel, and the piston is machined from aluminum. The valve is a conventional-type slide valve which originally operated on a teflon pad to eliminate lubrication needs. This system proved unsatisfactory because the pad kept coming loose. Therefore, the valve and pad were replaced with new ones machined from cast iron. The valve is operated, through a push rod, by a sealed ball bearing riding on a steel disk on the crankshaft. This has some advantages over a conventional eccentric because the disk can be shaped to give better control of valve timing. The engine can operate at any speed upto 600 RPM, although it performs best in the 200-300 RPM range. Maximum power output is 5 H.P.

The turbine is a Carling type 16A. It is rated at 9 H.P., but can be converted to 4.5 H.P. by plugging one nozzle for greater efficiency. In small sizes, turbines are inherently less efficient, but they have other advantages. The turbine contains a governor for precise speed control, operates with no lubrication, is mechanically very simple, operates quietly without vibration, and has a tremendously long life. Turbines are an industry standard, with proven reliability; whereas piston engines of small size tend to be models, hobby units, or experimental units.

The electrical generator is a standard 60 amp Chrysler automobile alternator. It is driven by the engine at a 1:6 ratio with a toothed timing belt. The only modification done to the alternator was to replace the stock pulley with a 20 tooth timing pulley.

Feedwater for the boiler is provided by a model 280 Cat pump which is a 3-piston pump capable of pressures upto 1000 psi and volume up to 3 gpm. It is driven by the engine with pulleys and V belt. A 12 volt solenoid valve controls feedwater flow to the boiler. The solenoid is switched on and off by the float valve on the boiler. An adjustable relief valve allows the pressure to be controlled, and provides for bypass of high pressure water when the solenoid valve is shut off. Also included in the feedwater system is a check valve at the boiler to prevent boiler pressure from escaping in the event of pump or piping failure.

Steam piping is 3/4" schedule 40 steel pipe, and all valves are rated 125 psi steam pressure or greater. Three-eighths inch copper tubing is used for high pressure feedwater and ½" plastic tubing is used for low pressure water. Drains are used at all appropriate points to allow complete system drainage for frost protection.

In addition to the alternator, the electrical system includes an ammeter with external shunt, expanded scale voltmeter, hour meter, automotive voltage regulator, and electronic tachometer. The tachometer is an automotive type and is controlled by ordinary ignition points operating on the main shaft of the engine.

A bank of four 12 volt deep cycle batteries is used for power storage, giving a combined capacity of approximately 400 amp hours. The home that the system is being tested in is wired for both 12 volt D.C. and 120 volt A.C. and has a wide variety of appliances designed or adapted to operate on 12 volt D.C. power. A 400 watt inverter is used to provide limited 120 volt A.C. power.

The charging rate can be controlled automatically with the voltage regulator, or manually by regulating the engine speed. A switch selects between the two. A feedwater control switch selects between automatic or manual on and off. A switch turns the tachometer on, and another switch turns on the alternator field winding. There also is a pressure switch on the steam line that automatically turns off the field current when pressure is two low to drive the engine at charging speed.

A wiring diagram of the electrical system is included in the appendix, and it is pretty much self explanitory.

PRELIMINARY CALCULATIONS FOR STEAM POWER PROJECT

Of particular importance to the design of the system was the matching of components of appropriate size and capacity.

It must be kept in mind that with steam, power-related ratings are not nearly as rigid as with electric or gasoline equipment. For instance, boilers are normally designed to produce 150% to 400% of their rating on an intermittent basis. They also can operate at a small fraction of their rating at efficiencies equal to or greater than their rating. Unlike gasoline engines, steam piston engines can operate at a small fraction of their rating with even greater efficiency than at their rated H.P. This is accomplished by maintaining high pressure, but using a very early steam cut-off time. Also, steam production by boiler, and consumption by engine, both vary greatly according to pressure being used, and amount of superheat being used. For these reasons these calculations are only approximate. They could easily vary by factors of approximately .7 to 1.5.

Boiler Specifications for Gas:

125 psi can be increased to 150 psi.

241 lb. steam per hour, maximum.

7 H.P. (based on standardised figure of 33.4 lb. steam/H.P./Hr.)

Actual steam rates vary from 5 to 100 lb./H.P./Hr. - (25-100 for small engines and turbines)

Efficiency - 70%.

Expected Performance with Wood Fuel:

Efficiency 50% (Higher stack temp. must be maintained for draft)

Lb. steam per hour - probably greater, because it isn't limited to BTU capacity of gas burner.

Using approximately 1200 BTU per lb. steam (from steam tables, approximate because of variable pressure, superheat, etc.)

Using 7000 BTU per lb. wood (an average figure for air dry and wet wood)

1 lb. wood @ 50% efficiency = 3500 BTU

3500 ÷ 1200 = approximately 3 lb. steam produced by 1 lb. wood or .34 lb. wood required for 1 lb. steam

Generator - 60 amp Automobile Alternator

60 amp x 14.7V (charge voltage) = 882 watts

746 watts/H.P. x .8 (estimated efficiency of alternators) = 597 watts/H.P.

597 watts/H.P. x .8 (estimated efficiency of belt drive) = 478 watts/H.P.

882 watts ÷ 478 watts/H.P. = 1.8 H.P. required

1.8 H.P. for alternators
+ .5 H.P. for feedwater pump and drive
2.3 Total H.P. Requirement, well within capacity of engine or turbine.

This power requirement, if verified by actual testing, would suggest decreasing engine RPM, or using an earlier cut-off timing for maximum efficiency with piston engine. With turbine, speed needs to be kept high for maximum efficiency.

Piston Engine Performance:

Can produce anywhere upto 5 H.P. depending on pressure, R.P.M. and steam cut-off.

Using mean effective pressure of 100 (125 psi boiler, fairly late cut-off timing)

R.P.M. = 500 = 500 power strokes/minute

3½" bore, 5" (.4167') stroke

$$\text{Indicated H.P.} = \frac{\text{MEP x } \overset{ft.}{\text{Stroke}} \text{ x piston } \overset{in^2}{\text{area}} \text{ x power strokes/min.}}{33000} = 6.07 \text{ H.P.}$$

Decreasing MEP (by decreasing boiler pressure, or using earlier cut-off timing) would yield any lower power desirable.

Estimated Steam Consumption rate is 30 lb./hr./H.P.

30 lb. steam/H.P./Hr.	30 lb. steam/H.P./Hr.
x 5 H.P maximum	x 2.3 H.P. required at 60 amp
150 lb. steam/Hr.	69 lb. steam/Hr.
Well within boiler capacity	Less than 1/3 boiler capacity. OK for good boiler efficiency

2.3 H.P. x 30 lb. steam/H.P./Hr. = 69 lb. steam/Hr.

69 lb. steam x .34 (lb. wood/lb. steam) = 23.5 lb. wood/hour at 60 amp output

Steam Turbine Performance: (Based on factory spec sheets and factory representative)

Can produce upto 9 H.P. on 2 nozzles

Can produce upto 4.5 H.P. on 1 nozzle

Basic steam consumption rate at 5000 RPM - 45.5 lb./Hr./H.P., (2 nozzles)
48 lb./Hr./H.P. (1 nozzle)

Efficiency is derated to 89% at ½ power output, therefore:

48 lb./Hr./H.P. derated for ½ power = 54 lb./Hr./H.P.

54 lb. steam/Hr./H.P.	54 lb./Hr./H.P.
x 4.5 H.P. maximum on 1 nozzle	x 2.3 H.P. required at 60 amp
243 lb. steam/Hr.	124 lb. steam/Hr.
Maximum limit of boiler capacity	Well within boiler capacity

2.3 H.P. x 54 lb./Hr./H.P. = 124 lb. steam/Hr.

124 lb. steam x .34 (lb. wood/lb. steam) = 42.2 lb. wood/hour at 60 amp output

Cat Pump Performance:

Maximum 3 gallons/minute at 1330 RPM maximum

3 gallons x 8.33 (lb./gal) = 25 lb/minute

25 lb./minute x 60 = 1500 lb./hour

Pump capacity is far in excess of the 69 to 124 lb. required, however, pump capacity and power requirements are directly proportional to speed, so it can be matched to any lower water requirements.

Solenoid Valve Performance:

Must be able to pass feedwater fast enough to keep up with maximum possible boiler output.

Maximum expected water requirement with turbine = .25 gal./min.

.25 gal./min. x 2 (safety margin) = .5 gal./min.

From water flow charts in Skinner Valve engineering tables:

.5 gal./min. with 25 psi pressure drop (150 psi water pressure for 125 psi boiler pressure) requires valve with .1 Cv factor.

Skinner valve V52LB2125 has Cv factor of .18 (more than required) and is the only one with greater than .1 Cv factor that is also rated for 125 psi operating pressure differential.

Remaining components of the system are not critical as to size and capacity.
A complete list of all components is listed in the appendix.

TESTING

After the power plant was operational, and all components were determined to be performing properly, six four-hour tests were conducted. Three each for the turbine and the piston engine. The fuel used for all the tests was Douglas-fir and larch mill ends with an average moisture content of 27%. Complete results of the tests are in the appendix.

The following observations and deductions are based on the test results after the plant had been warmed up and started. I haven't included the fuel used in start-up because a normal charging would last much more than 4 hours and therefore, the start-up wood would be less significant. The appendix does include some wood consumption figures, including start-up, based on a 10-hour run, and it shows the fuel consumption to be approximately 10% greater.

Average results of all the tests showed that the turbine consumed 114 pounds of wood for each KWH of electricity produced. The piston engine used 65 pounds per KWH. The turbines great consumption required the boiler to be pushed to its maximum capacity, and it was very difficult to maintain boiler pressure.

A simple friction brake was used to measure horsepower output at 600 RPM with 90 psi steam pressure, and at 320 RPM with 55 psi pressure (the conditions shown by the tests to yield 775 watts and 462 watts respectively). The results were 1.8 H.P. and 1.1 H.P. resulting in 431 watts and 420 watts per H.P., for an average of only 426 watts per horsepower; or 2.3 H.P. required per KW. This was a surprisingly low figure, and shows efficiency of the alternator and belt drive to be only 57%.

The test results yield the following information on steam consumption for the two engines:

Test #	Lb. steam	Watt Hr.	Lbs. steam/Hr.	Ave. Watts	H.P.	Lb. steam/H.P./Hr.
1 Turbine	908	3007	227	752	1.8	126
2 "	900	2968	225	742	1.7	132
3 "	816	2311	206	578	1.4	147
4 Engine	650	3155	163	789	1.9	86
5 "	500	2296	125	574	1.3	96
6 "	358	1857	90	464	1.1	82

Steam consumption in all cases was much greater than expected. It may be possible to improve the performance of the piston engine somewhat with different valve timing, but nothing can be done to improve the turbine. With the piston engine, steam consumption is slightly better at lower output, suggesting that it would be more economical to charge at a lower rate for a longer period of time.

Comparing water and wood consumption shows that steam produced per pound of wood ranges from 2.72 pounds steam per pound of wood to 3.33 pounds steam per pound of wood. The worse rates were when the boiler was pushed hard while driving the turbine. The higher rates occurred when the boiler was producing at a lower output. This also suggests that with this system it is preferable to charge more slowly. Another advantage to running the system at a lower rate is that the boiler was found to smoke very heavily when pushed hard, and burned much cleaner when running easily (but still not very clean by modern wood combustion standards).

Actual construction of the system was not exceptionally complex, although it required a moderate degree of familiarity with metal working, pipe fitting, and electrical wiring.

Construction of the firebox was a relatively straightforward welding project. It is a rectangular box made from ¼" steel welded the full length of all the corner seams to make it air tight. It has an ash door and a fuel door on the front, and a round opening in the top leading to the boiler shell. There is a grate inside to support the wood, and on the side near the top is a draft opening with a flap to control the rate of burn. There is a baffle inside the firebox to direct the combustion air down the side and under the grate so that the air feeds the fire from below. This baffle also serves to preheat the air. The entire firebox (except for the baffle) is lined with 3 inches of castable block mix from A.P. Green Refractories Co. It is a lightweight castable refractory with very good insulating properties. The area subject to damage by firewood was also lined with firebrick to protect the refractory. Casting the refractory was done by laying the box on one side and pouring the refractory 3" depth on the bottom. After drying, the procedure was repeated for the side, etc. There also is a cylindrical section between the firebox and boiler to increase the combustion space. This section was also lined with refractory, and it includes a door to permit inspection of the bottom of the boiler. For further details, see the drawings and photographs in the appendix.

The boiler firebox unit could be improved quite a bit. The firebox needs a much longer flame travel area to allow for combustion to be completed before the gases enter the firetubes. In the test model, when the flames enter the relatively cooler firetubes, heat transfer is sufficiently effective to quench the flame. This results in gases and carbon particules being exhausted unburned.

The engine, alternator, and feedwater pump are all located on a solid steel table next to the boiler. All the items are bolted securely to the table, as there is a moderate amount of vibration at some speeds. The layout is best explained by the pictures and drawings in the appendix. The electrical controls are all located in a steel box on the wall behind the unit.

OPERATING PROCEDURE

The operating procedure described here is only intended to give a general idea of what is involved. Every system will differ somewhat, and no one should attempt to work with steam without a much more thorough understanding than can given in this report.

The procedure is as follows:

1. Fill boiler to the center of water gauge. Approximately 30 gallons.

2. Start fire in firebox and feed it quite rapidly until pressure gauge shows approximately 100 psi. Time required to get up steam is about 20 - 40 minutes.

3. Spin the engine pulley, and at the same time open the steam valve slightly to start engine running. Immediately reduce engine speed (with the steam valve) to the slowest possible without stalling, and continue at this speed until the engine gets hot, the exhaust gets fairly dry, and there is no evidence of knocking from condensation in the cylinder.

4. Increase the engine speed and turn on the alternator field switch to start charging. When the switch is turned on, the steam valve must be opened more to maintain speed.

5. Open the drain valve on the outlet of the solenoid valve to bleed air from the pump. Turn feedwater switch to manual "on" position to keep solenoid valve open. After no more air is present, close valve and place switch in manual "off" position.

6. Adjust relief valve on pump 'till water pressure gauge shows 150 psi, then return switch to automatic position. As long as pump is operating properly, gauge will show 150 psi whenever solenoid valve is closed, and will show the same as boiler pressure whenever the valve is open.

7. Adjust charge rate one of two ways:

    a. Manual: place voltage control switch to manual position and adjust engine speed to obtain desired voltage. In this position, voltage will gradually increase as battery charge increases, but engine speed will remain constant.

    b. Automatic: place voltage control switch to automatic position. This will prevent excessive voltage. Adjust engine speed slightly higher than the minimum speed needed to maintain proper voltage. In this position, engine speed will gradually increase as battery charge increases, but voltage will remain constant.

8. Throughout operation, the following must be monitored periodically:

    a. Add fuel as required to maintain boiler pressure.

    b. Monitor boiler pressure to be certain automatic damper control is operating properly.

    c. Monitor waterglass gauge and feedwater pressure gauge to be certain feed system is functioning properly. This is very important, as low water level in the boiler can cause boiler steel to overheat and weaken, possibly leading to an explosion.

    d. Monitor voltage and engine speed and adjust steam valve to maintain desired speed and voltage.

9. When charge is nearly complete, let fire burn down. Boiler will still maintain pressure for some time, and engine can be kept running until pressure drops too low.

10. At his point, close steam valve, turn off all switches and allow boiler to cool till pressure drops to 5-20 psi.

11. Open blowdown valve and allow pressure to blow out the entire boiler contents to clean it of residue.

12. Open all valves and drains to allow the entire system to dry out. This is particularly important in winter to prevent freezing.

13. As an alternative to 11 and 12, during warmer weather, the system may be left full. In that case, once or twice during operation open the blowdown valve just until the water level reaches the bottom of the gauge and let the pump refill it. This is best done when fire is not exceptionally hot.

Future monitoring of the system will take the same form as the tests included in this report. The tests will be performed periodically, particularly whenever any changes or improvements are made.

The same battery bank that is used for this project has been charged numerous times with a gasoline powered generator using a 5 horsepower Wisconsin industrial air cooled engine. Two fuel consumption tests were performed on this generator also, to serve as a base of comparison for the steam generator. One test used 1.5 gallons of gasoline to generate 3075 watt-hours, and the other test used 1.33 gallons to generate 2972 watt-hours. This results in 0.49 and 0.45 gallons per KWH, or an average 0.49 gallons per KWH. At 120,000 BTU per gallon for gasoline, the result is 56,400 BTU of gasoline to produce one KWH (3,413 BTU) of electricity. This gives an overall efficiency of 6%.

The efficiency of the boiler can be calculated from the test data. Driving the turbine, it produced an average of 2.78 pounds steam per 1 pound wood. With the piston engine, it produced 3.17 pounds steam per pound wood. Using the values of 7000 BTU per pound of wood (from Montana State Cooperative Extention Service) and 1200 BTU per pound of steam (from steam tables, approximate because of variable pressure, superheat, etc.) we get the following resutls:

2.78 lb. steam x 1200 BTU = 3336 BTU
3336 BTU ÷ 7000 BTU (for wood) = 48% boiler efficiency running turbine

3.17 lb. steam x 1200 BTU = 3804 BTU
3804 BTU ÷ 7000 BTU = 54% boiler efficiency running piston engine

Complete system efficiency is as follows:

Turbine

114 pounds wood per KWH
x 7000 BTU per pound
798,000 BTU input per KWH output

3,413 BTU (value per KWH) ÷ 798,000 = .0043 or .43%

With 48% boiler efficiency, and 57% alternator and drive efficiency, the remaining energy loss is accountable to the turbine which is only 1.6% efficient.

Piston Engine

65 pounds wood per KWH
x 7000 BTU
455,000 BTU input per KWH output

3,413 ÷ 455,000 = .0075 or .75%

With 54% boiler efficiency, and 57% alternator and drive efficiency, the remaining energy loss is accountable to the piston engine which is 2.4% efficient. This is quite low, and at least one manufacturer of small engines (quite expensive - $1800) claims 4% to 5%. Larger stationary slide valve engines that were common in the past operated in the range of 7% to 10% efficiency. This suggests that the greatest improvement in this system would result from improvement or replacement of the engine.

The wood fuel used is mill waste so there is no additional energy requirement to prepare it for boiler use. The only energy expenditure involved is fuel for delivery, and it is statistically insignificant since less than one gallon of gasoline is required to deliver 8000 pounds of wood.

The gasoline generator is 8 times more efficient than the piston steam system; however, it uses non-renewable fossil fuel rather than waste products from renewable sources. There are some other advantages to the steam system that will be discussed in the next section on economics.

ECONOMICS

The total cost of the project was $7,792.03. This economic analysis is based on the piston engine which is the more efficient of the two tested. The actual cost of the final piston engine system is somewhat less. Eliminating components not used in the final system, such as the turbine; and eliminating transportation, research, and construction time that would not be required to build an approximate copy of this system, the cost would be $5,562.00. This economic analysis will deal with the actual costs directly applicable to this final system. The complete costs of the grant project will be analyzed in the section on grant administration.

Total cost breakdown for the piston engine is as follows. Complete equipment list and specifications is in the appendix.

Boiler	$1325.00
Piston Engine	500.00
Feed Pump	150.00
Solenoid Valve	44.44
Steel for Firebox & Table	233.70
Firebrick & Refractory	77.25
Batteries	279.96
Pipe, Valves, & Fittings	160.00
Alternator	39.00
Misc. Parts & Supplies	481.65
Building	300.00
Contracted Welding	151.00
Labor & Research @ $3.00/hour	1500.00
Transportation	300.00
Phone, etc.	20.00
Total Cost	$5562.

The life of the equipment is unknown. The boiler shell is the only major component that is not generally repairable and would require complete replacement when it wears our. It should be expected to last anywhere from 20 to 40 years. The rest of the components would not be expected to last that long, but they are repairable. Engine bearings and rings are easily replaced, and replacement valve parts can be made as needed. Individual pipes, fittings, valves, gauges, etc. can be replaced as needed. For computation purposes, an estimated lifetime of 20 years (a conservative figure) will be used, and an estimated $50.00 per year repair costs will be used.

The maintenance requirements are quite small and generally require an average of approximately ½ hour per day of operation, and essentially no cost. The maintenance requirements are:

1. Every 30 to 40 hours - clean firetubes with flue brush, and empty ashes (5-10 gallons which are disposed of in the garden as a soil building resource).

2. Blowing down and draining the system each time it is used.

3. Periodically adjusting belt tension.

4. Monitoring water quality. The main consideration is PH. The water must be neutral to slightly alkaline. The water used for this project fits this requirement, and no water treatment is used.

Since there is essentially no maintenance cost, average yearly costs are $281 for equipment (total cost depreciated over 20 years), $50 for repairs, and $20 for license fees (full details on State regulations and licensing may be obtained from State of Montana Division of Workers Compensation, 815 Front St., Helena, MT 59604) That is a total of $351 per year.

The fuel used is mill waste which is available at a delivered cost of $20 per 8000 pound load. No additional cost is involved since the mill ends are already in small pieces, and they are stored in piles at no additional cost.

The approximate electrical consumption of this home is 500 kilowatt-hours per year. The test results showed 65 pounds of wood per KWH, or 32,500 pounds of wood per year. At the current price, that would be $81 per year for wood. If it were necessary to purchase cordwood at the current local price of $50 per cord, then 13 cords would be required at a cost of $650 per year.

Total Yearly Costs

Mill Ends		Cordwood
315	Yearly Equipment Costs	315
81	Fuel	650
$396	Total	$965
.79	Cost per KWH	1.93

By comparison, the same power generated by a gasoline engine would cost as follows:

Engine cost $150. Design life of engine is 1000 hours for heavy duty models, and 300-500 hours for aluminum light duty engines. At an average charge rate of 35 amps, a heavy duty engine would last 1 year with above power consumption.

The gasoline generator used .47 gallons per KWH.

Total Yearly Cost for Gasoline Engine

$150	Engine cost with 1 year life expectancy
40	Oil change every 25 hours at $1.00 per quart
305	Gasoline
$495	Total
.99	Cost per KWH

Public utilities generated electricity in this area costs approximately 4½ cents per KWH which is only 5% as much as wood or gasoline produced electricity. However, there are many places in rural Montana (particularly in the mountains) where commercial power is either not available, or is prohibitively expensive to have power lines installed. To get commercial power to this project site would cost approximately $50,000. That would pay the operating costs of the steam power unit for about 125 years.

It must be emphasized that this system is only advantageous where power consumption is low, or where there is no other alternative. As an example, figures based on power consumption 100 times greater - 50,000 KWH per year show the following costs:

Mill Ends			Cordwood	
315		Yearly Equipment Costs	315	
8100	(406 loads)	Fuel	65000	(1300 cords)
$8415		Total Cost Per Year	$65315	

That amount of power purchased at 4½ cents per KWH would cost $2250. Compared to using mill ends, using commercial power would save $6165 per year; enough to pay for the power line in about 8 years. This amount of production would actually cost even more with wood, because a much larger system would be required. It would have to run continuously at an average of 5.7 kilowatts.

All the above calculations are based on current fuel and electricity prices, which of course will change. Gasoline can probably be expected to increase the most over the next several years, making it less competitive with wood. As long as mill waste is available, the wood cost will not likely change very much. This supply could of course be cut off at any time, making it necessary to use cordwood. Firewood is very abundant in this area, and the price is not likely to change very greatly. In fact, if purchased by the log truck load, it's current cost is only about $30 per cord.

WORK SCHEDULE

The project took much longer to complete than intended. It was originally intended to take five months to complete the system, and several months more for complete testing. The expected and actual work schedule are shown below.

Beginning date of contract - April 4, 1982

	Proposed Completion Date	Actual Date
Milestone 1 Prepare final plans for boiler and firebox	June 4, 1982	May 7, 1982
Milestone 2 Prepare final plans for complete system	June 4, 1982	May 7, 1982
Milestone 3 Construct and test firebox and boiler	July 4, 1982	Dec. 11, 1982
Milestone 4 Construct complete generating system	Aug. 4, 1982	June 7, 1983
Milestone 5 Conduct performance tests	Jan. 4, 1983	June 30, 1983
Milestone 6 Prepare and submit final report	Jan. 4, 1983	Oct. 4, 1983

The large delay on Milestone 3 was a result of several factors. The boiler plans had to be approved by the State boiler board prior to construction, and they delayed several months before reviewing the plans. At that time they advised that the plans would have to be certified by a registered engineer, and this was found to be prohibitively expensive. The only reasonable alternative was to purchase a used boiler, and the grant was amended to authorize the additional expense. The overall delay resulting from the board action was about six months. Some additional delay was a result of delays in delivery of some supplies and materials. Most of the delay would be avoidable by planning on the use of a commercial boiler and, in the case of a used boiler, locating it in advance. Used power boilers in small size are quite rare, but are well worth looking for because new ones cost $3500 to $5000.

BUDGET

The total project cost was $7792.03. The grant was for a maximum of $3750.00. Below is a summary of the budget, separating the expenditures according to the source of the money.

	GRANT	GRANTEE
Salaries for Labor & Research Time	60.00	3000.00
1000 hours at $3.00 per hour donated by grantee		
Contracted Welding on Firebox	151.00	
Contracted Drafting for Preliminary Report	40.00	
Supplies and Materials		
Pipe, Valves, Fittings, etc.	186.90	
Steel for Firebox and Table	233.70	
Firebrick and Refractory	77.25	
Solenoid Valve	44.44	
Stove Pipe	24.15	
Misc. Supplies - Wire, Pulleys, Gauges, Controls, etc.	307.23	214.40
Phone, Postage, Office Supplies		120.00
Transportation for Picking Up Equipment & Supplies	100.00	300.00
Equipment		
Boiler	1325.00	
Alternators	78.00	
Steam Piston Engine	500.00	
Steam Turbine	300.00	
Feed Pump	150.00	
Batteries - 4 Deep Cycle Marine Batteries	139.98	139.98
Building to House Equipment		300.00
Total Grant Expense	$3717.65	$4074.38
Total Grantee Expense	4074.38	
Total Project Cost	$7792.03	

CONCLUSIONS AND RECOMMENDATIONS

The piston engine system was expected to use 28 pounds of wood per KWH, but actually used 65 pounds, therefore, the system is not as desireable as expected. However, for a small system such as this, where the only other alternative is gasoline power, it can be cost competitive with gasoline. It also uses a renewable fuel source, and is much quieter in operation. On the minus side, considerably more work and knowledge is involved in operating the steam system than simply filling a gas tank and starting an engine. Also, Montana has fairly extensive laws governing steam boilers, designed primarily to protect the public. Anyone planning on using steam power should investigate these laws and determine how they apply to the particular project being planned, by by contacting the Montana Division of Workers Compensation (See page 23). A system such as this would be adaptable to any location with abundant wood supplies. It would be particulary desirable where there is a continuous supply of waste material, such as the mill ends used in this project.

Although the system performs adequately as it is now, there is a lot of room for improvement. As mentioned earlier, the boiler could be made more efficient and cleaner by having a longer flame path. Current research into high efficiency woodstoves may yield designs that could be adapted to power boilers to greatly increase boiler efficiency. As mentioned earlier, the engine seems to be particularly low efficiency. It may improve through further valve adjustments. There are other engines that would probably use less steam, but some of them are very expensive, and some wouldn't last as long as the present engine. There is a lot of room for further research on engine designs in the small size range. Most of the small engines available are basically working models with little interest on high efficiency. Five to seven percent efficiency should be easily attainable, and that would make the entire system 2 to 3 times more efficient.

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PERFORMANCE TESTS
ON
STEAM POWER PLANT

3 4-hour tests on steam turbine
3 4-hour tests on piston engine

Average results:

The turbine used 114 pounds of wood/KWH during the test.
The piston engine used 65 pounds/KWH during the test.

Adding in the wood used for start-up, the wood consumption during an average 10-hour run would be:
122 pounds/KWH for the turbine
74 pounds/KWH for the piston engine

All the tests were done with mill ends with an average moisture content of 27%

Test # 1

Engine Turbine

Remarks To test performance at max. rate of 60 A. Rate had to be dropped to 40 A to prevent excessively high voltage. It was very difficult to maintain boiler pressure at 60 Amps.

Timer Hours	R.P.M.	Boiler Pressure	Engine Pressure	Water Temp.	Engine Steam Temp	Amps	Volts	Average Watts	Lbs. Wood Added	Gal. Water Added
3.4	Start-up			59						
3.9	5000	84	80		330	60	13.2		50*	
4.4	5000	105	80		345	62	14.2	836.2	40	10
4.9	4900	100	80		325	59	14.8	876.8	40	15
5.4	5000	85	80		330	60	15.6	904.6	50	15
5.9	5000	90	80		325	60 40	16.0 15.1	948.0	40	17
6.4	3000	85	70		325	40	15.1	604.0	40	10
6.9	3000	100	68		335	38	15.3	592.7	40	15
7.4	3000	95	70		330	40	15.8	606.7	30	15
7.9	3000	75	70		320	41	16.0	644.0	40	12
						Totals		Watt-Hr	Wood	H_2O
								3006.5	330	109
								start-up	+ 50* 380	

Test #: 2

Engine Turbine

Remarks To test performance at 50 Amp charge rate

Timer Hours	R.P.M.	Boiler Pressure	Engine Pressure	Water Temp.	Engine Steam Temp	Amps	Volts	Average Watts	Lbs. Wood Added	Gal. Water Added
7.9	Start-up			47						
8.4	3800	100	74		320	50	12.8		55*	
8.9	3800	105	74		320	52	13.4	668.4	50	10
9.4	3700	100	73		318	47	13.9	675.1	40	15
9.9	3800	115	76		320	50	14.3	684.2	40	10
10.4	3800	95	76		322	50	15.1	735.0	40	15
10.9	3800	100	79		318	51	15.7	777.9	40	15
11.4	3700	80	76		320	49	15.9	789.9	50	10
11.9	3800	105	79		320	50	16.2	794.6	40	15
12.4	3800	80	79	↓	316	50	16.2	810.0	15	18
							Totals	Watt-Hr	Wood	H_2O
								2967.6	315	108
								Start-up	+55*	
									370	

Engine Turbine

Remarks To test performance at constant 40 Amp charge rate

Timer Hours	R.P.M.	Boiler Pressure	Engine Pressure	Water Temp.	Engine Steam Temp	Amps	Volts
12.4	Start-up			53			
12.9	3000	90	68		320	40	12.5
13.4	2800	100	67		320	38	13.2
13.9	3000	110	70		325	40	13.6
14.4	3000	105	70		320	42	14.0
14.9	3000	100	70		318	41	14.7
15.4	3000	110	70		315	39	14.9
15.9	3000	110	72		325	40	15.2
16.4	3000	105	73		320	40	15.8
16.9	3000	80	73		320	40	15.8
							Totals

Average Watts	Lbs. Wood Added	Gal. Water Added
	60*	
500.8	40	10
522.8	40	10
566.0	40	15
595.4	30	10
591.9	40	15
594.6	40	15
620.0	40	15
632.0	30	8
Watt-Hr	Wood	H_2O
2311.4	300	98
start-up	+ 60*	
	360	

Test # 4

Engine Piston

Remarks To test performance at 50 Amps

Timer Hours	R.P.M.	Boiler Pressure	Engine Pressure	Water Temp.	Engine Steam Temp	Amps	Volts	Average Watts	Lbs. Wood Added	Gal. Water Added
17.2	Start-up			51						
									55*	
17.7	600	100	87		345	50	14.2			
								707.8	30	10
18.2	560	85	85		345	48	14.7			
								730.3	30	5
18.7	600	100	90		350	50	15.1			
								783.1	20	10
19.2	620	100	94		350	52	15.6			
								795.2	30	10
19.7	600	105	90		355	49	15.9			
								802.1	20	10
20.2	600	98	94		350	50	16.5			
								825	20	5
20.7	620	110	96		345	50	16.5			
								825	30	10
21.2	600	90	94		345	50	16.5			
								841.5	15	18
21.7	600	100	96		345	52	16.5			
								Watt-Hr	wood	
								3155	195	78
								Startup	+ 55*	
									250	

Engine Piston

Remarks To Test Performance at 40 Amps

Timer Hours	R.P.M.	Boiler Pressure	Engine Pressure	Water Temp.	Engine Steam Temp	Amps	Volts	Average Watts	Lbs. Wood Added	Gal. Water Added
23.1	Start - up			55						
23.6	400	100	72		330	40	13.2		60*	
24.1	440	115	75		325	43	13.8	560.7	20	5
24.6	400	100	72		330	38	14.2	566.5	20	5
25.1	425	105	76		332	42	14.3	570.1	20	10
25.6	380	90	69		340	37	14.5	568.6	20	5
26.1	400	105	75		330	40	14.7	562.3	30	10
26.6	400	105	76		330	41	14.8	597.4	20	10
27.1	380	100	72		330	38	14.8	584.6	20	5
27.6	400	100	75		330	40	15.0	581.2	20	10
						Totals		Watt-Hr	Wood	H$_2$O
								2295.7	170	60
								startup	+ 60*	
									230	

Test # 6

Engine Piston

Remarks To Test performance at 30 Amps. This test continues directly from test # 5, therefore no start-up time involved

Timer Hours	R.P.M.	Boiler Pressure	Engine Pressure	Water Temp.	Engine Steam Temp	Amps	Volts	Average Watts	Lbs. Wood Added	Gal. Water Added
27.6	320	105	53	55	310	30	14.8			
								448.5	20	5
28.1	320	100	55		305	30	15.1			
								477.3	10	5
28.6	330	110	58		310	33	15.2			
								478.8	10	5
29.1	320	100	57		310	30	15.2			
								435.9	10	5
29.6	300	85	52		320	27	15.4			
								455.9	10	5
30.1	320	105	57		315	32	15.5			
								483.5	20	5
30.6	320	100	55		310	30	15.7			
								456.7	10	5
31.1	310	95	54		310	28	15.8			
								477.2	20	8
31.6	325	100	57		305	32	16.0			
						Totals		Watt-Hr.	wood	H₂O
								1856.9	110	43

EQUIPMENT LIST AND SPECIFICATIONS

BOILER - Eclipse Lookout Co., Chattanooga, TN
Model 7D, 7 H.P., max. W.P. 125 psi, includes gauges, relief valve, McDonnell & Miller float control.

PISTON ENGINE - Therm-A-Volt, Republic, WA
Prototype, 3½" bore, 5" stroke, upto 5 H.P., upto 600 RPM

STEAM TURBINE - Carling Turbine Blower Co., Worchester, MA
Type 16A, 9 H.P., 3200 RPM, 5000 RPM max.

FEEDWATER PUMP - Cat Pumps, Minneapolis, MN
Model 280, 3-piston, 3 GPM, max. pressure 1000 psi, max. 1330 RPM

SOLENOID VALVE - Skinner Valve, New Britain, CN
Model V52LB2125, normally closed, 12 volt, Cv factor .18, 125 psi operating pressure differential

CHECK VALVE - Standard plumbing brass valve

PRESSER CYLINDER FOR DAMPER CONTROL - Wolf, max. pressure 200 psi, 3/4" bore, 2" stroke, 44 lb. push at 100 psi

VALVES - All teflon seat ball valves, 150 psi working steam pressure, 1" main steam valve and blowdown valve, ½" and 3/8" all others

FEEDWATER PRESSURE RELIEF VALVE - Grainger, #1P786, 5-300 psi

ALTERNATOR - Chrysler Automotive, rebuilt 60 amp

VOLTAGE REGULATOR - Standard Delco Automotive regulator

VOLTMETER - Surplus Center, #21-958, 9.5-16 volt DC

AMMETER - Herbach & Rademan, #TM22K654, 0-200 amp

SHUNT FOR AMMETER - Airborne Sales, #1792R, 2 in parallel cause ammeter to read 60A full scale

HOURMETER - Herbach & Rademan, #G10-100, 12V. DC

THERMOMETER - Herbach & Rademan, #W1-408, 50° - 500° F

PRESSURE SWITCH - Allen Bradley, #836T-T252J, adjustable 0-75 psi

TACHOMETER - Airborne Sales, #4220 electronic

MISC. PRESSURE GAUGES, SWITCHES, 4 GAUGE CABLE, ETC. - Airborne Sales, Surplus Center, and Herbach & Rademan

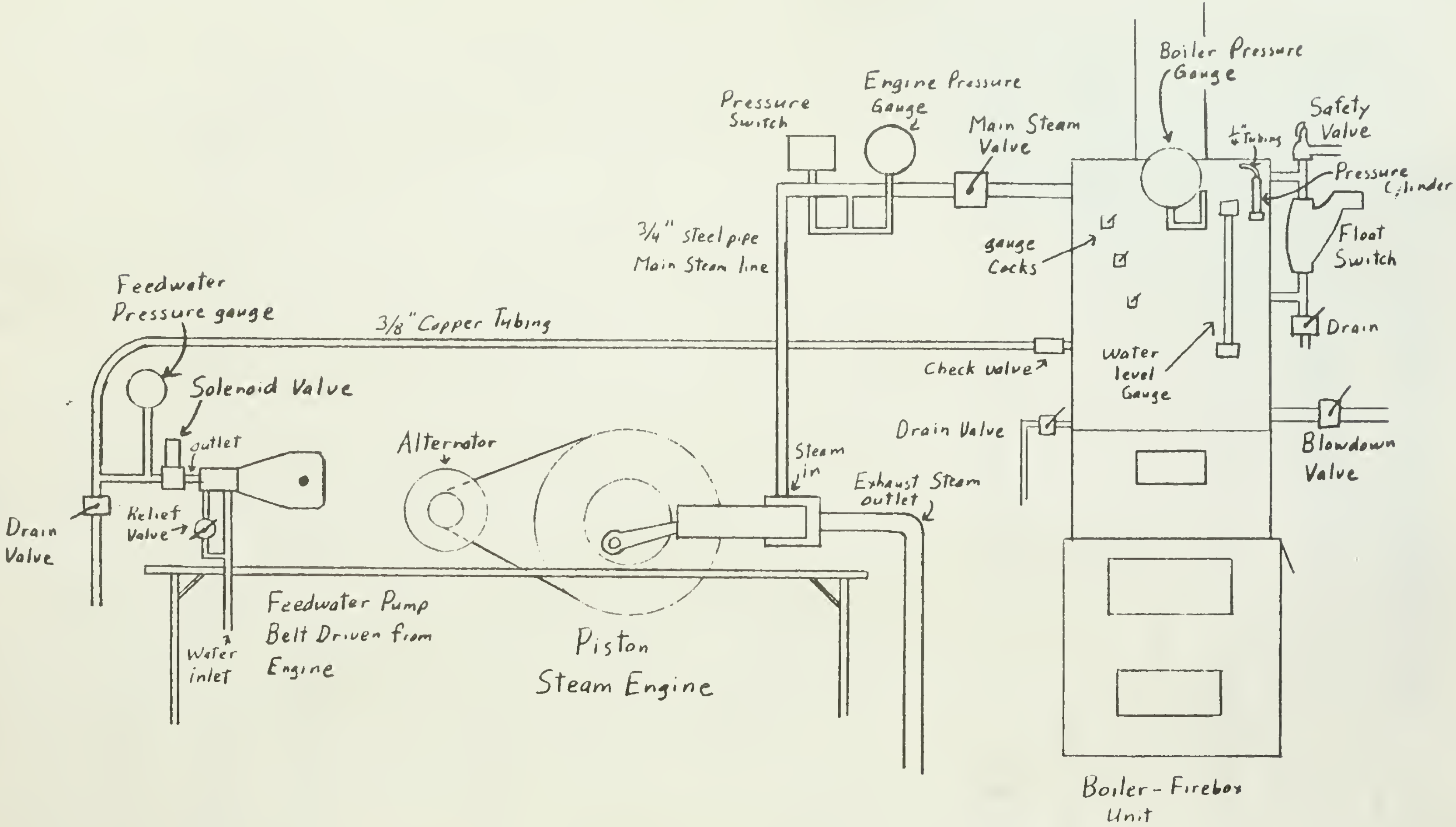
TIMING BELT PULLEY - Dodge Div. Reliance Electric, 20 tooth, 120 tooth pulley and belt were included with steam engine

MISC. PULLEYS & BELTS - From local hardware and Grainger

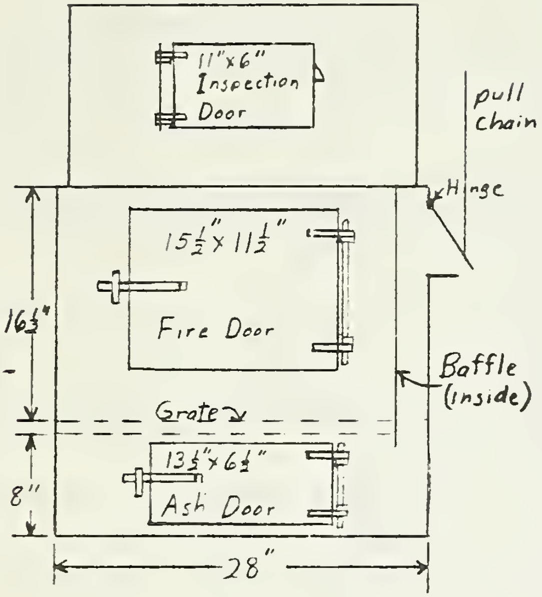
STEAM PIPE - Schedule 40 steel pipe

FEEDWATER PIPE - 3/8" copper tube

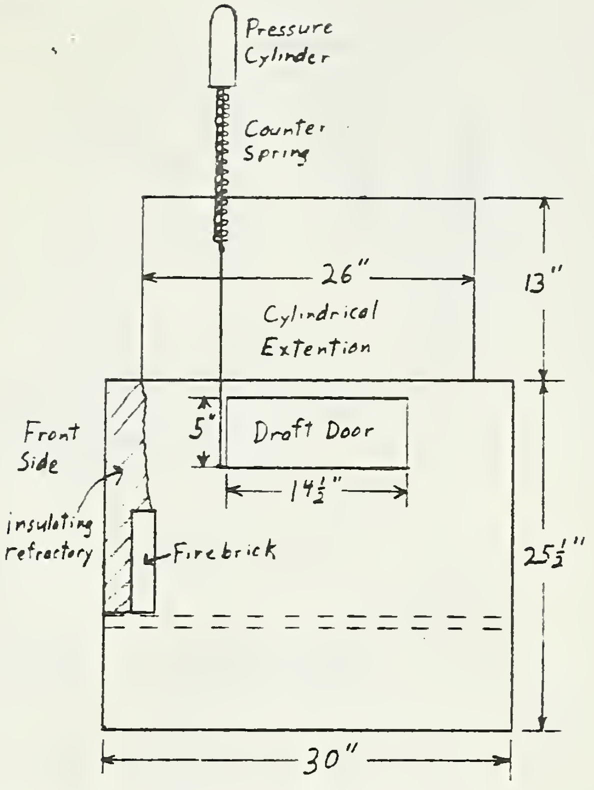
COMPLETE SYSTEM DRAWING



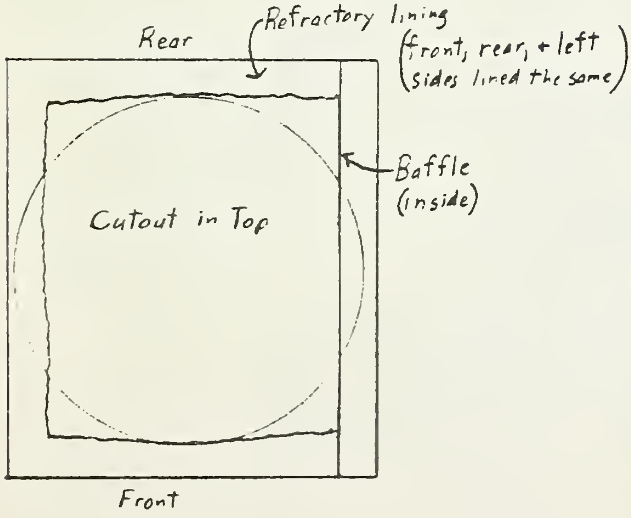
FIREBOX



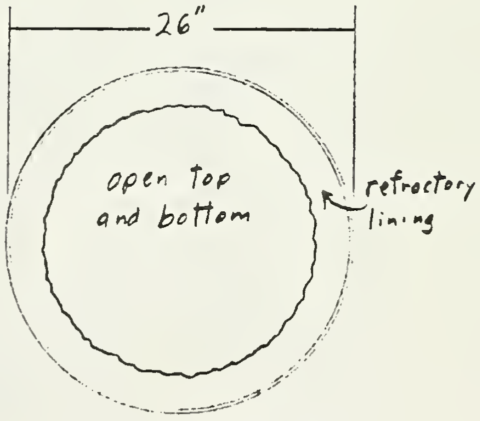
Front View



Right Side View



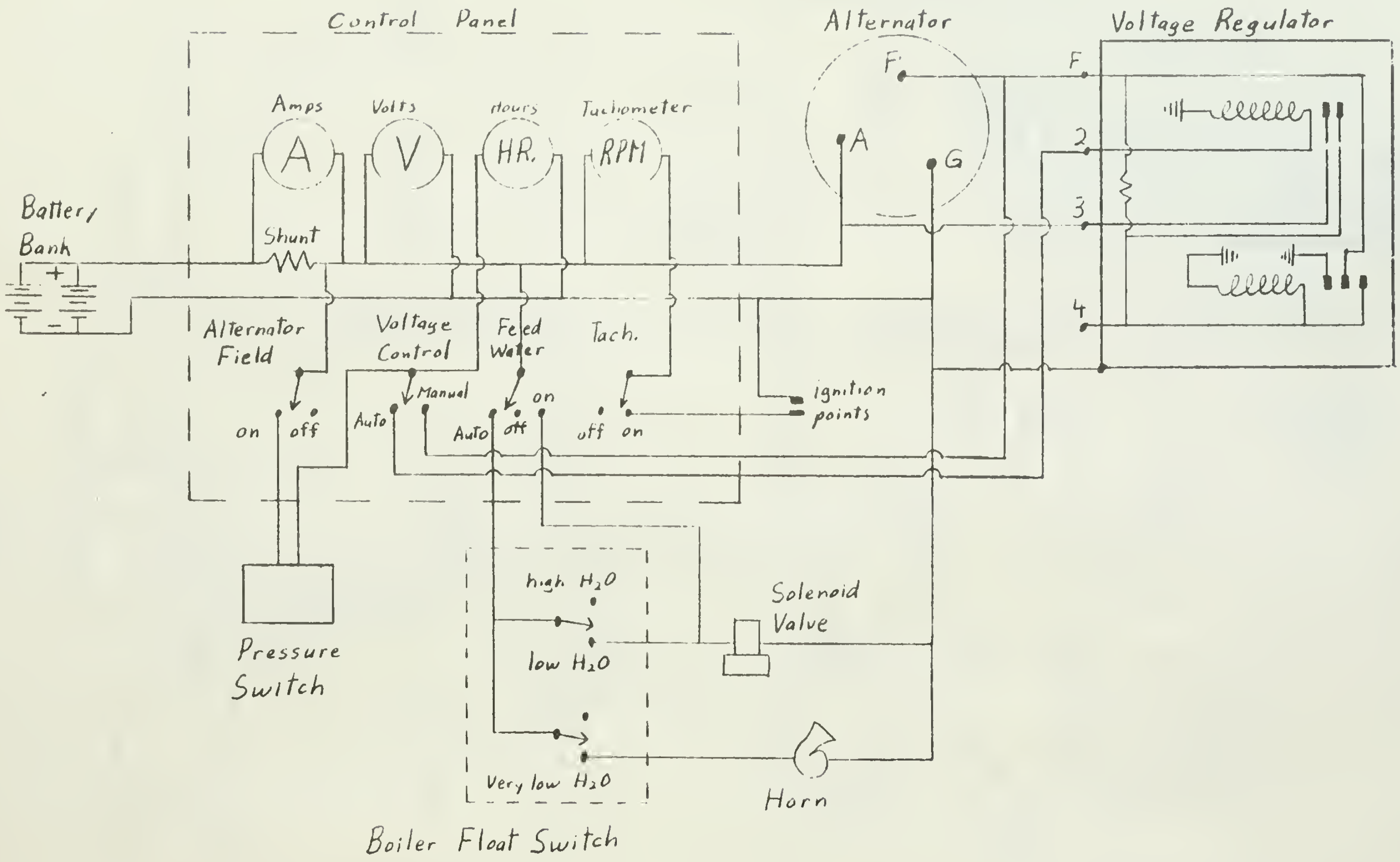
Top View



Cylindrical Extention

Top View

WIRING DIAGRAM



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Engineers and Mechanics Guide, (Audel)

Power Plant Engineers Guide, Grahm (Audel)

Steamboats and Modern Steam Launches, Durham
This is the only source that deals extensively with small size steam power.

A Treatise on the Steam Engine, Farey

Steam Engine Theory and Practice, Ripper

Handbook of Chemistry and Physics, Chemical Rubber Publishing Co.

Live Steam, (magazine), Traverse City, Michigan

Semple Steam Power - Installation, Maintenance, Operation Manual, Semple Engine Co., Inc., Saint Louis, MO

OTHER EQUIPMENT SUPPLIERS

Semple Engine Co., P.O. Box 6805, Saint Louis, MO 63144
Steam engines and boilers

Tiny Power, P.O. Box G, Tehachapi, CA 93561
Steam Engines

Coles Power Models, P.O. Box 788, Ventura, CA 93001
Model engines, some large enough for power production

Hypro Pumps, 375 Fifth Ave., N.W., New Brighton, Saint Paul, MN 55112
Piston pumps suitable for feedwater

Western Metal Products Inc., 2321 Waring Drive, Agoura CA 91301
Custom-built code boilers and fireboxes

Columbia Boiler Company, Pottstown, PA 19464
Firetube boilers

Parker Boiler Company, 2035 E. 37th Street, Los Angeles, CA 90058
Watertube boilers

Automatic Switch Company, Florham Park, New Jersey 07932
Solenoid Valves

MISC. EQUIPMENT AND SUPPLIES AVAILABLE FROM

Herbach & Rademan, 401 East Erie Ave., Philadelphia, PA 19134
Surplus Center, P.O. Box 82209, Lincoln, NB 68501
Airbourne Sales, P.O. Box 2727, Culver City, CA 90230
Grainger's, E. 5706 Broadway Ave., Spokane, WA 99206

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